

Beam Position Monitors

Main Linac

Beam position monitors will be placed at each of the approximately 800 quadrupoles in the two main linacs. BPMs will be included in the cryomodule. They shall report the position of each bunch in every bunch train.

Table 1. Main Linac Beam Position Monitor Requirements

Parameter	Requirement	Comments
Quantity	~800	Every quadrupole
Environment	Cold	In cryomodule
Aperture	60 mm – 70 mm	BPMs not to be limiting aperture
Resolution	0.5 micron	
Stability	<10 microns	Over cryomodule thermal cycling
Temporal resolution	bunch-by-bunch	

BPM pickups must be compatible with superconducting RF cryomodules. In particular during fabrication/assembly they must be cleanable with standard techniques to prevent contamination of the cryomodule.

Beam Position Sensor Technologies

There are two candidate solutions for the beam position pickup sensor. Both are based on resonant cavities. The “conventional cavity” BPM relies on dipole modes of a resonant cavity which is essentially a pillbox. The “re-entrant cavity” BPM relies on the dipole resonant mode of a coaxial resonator where the beam duct is the center conductor. Both candidate technologies require further R&D to be established as a proven solution to all of the system requirements.

Cavity BPM

By “cavity BPM” we mean essentially a pillbox-type cavity BPM with common-mode free coupling to external electronics. That is, the signal produced at the position output coupler is essentially that of the dipole mode and is therefore proportional to the product of beam charge and beam position. Cavity BPMs show extremely good resolution and stability. Examples are those designed at BINP and studied extensively at KEK’s ATF and those built by KEK’s Shintake and evaluated at SLAC’s FFTB. These feature dipole-mode couplers that reject the cavity monopole modes. This reduces the dynamic range required to achieve sub-micron resolution and is thought to yield excellent accuracy and stability. At C-band resolution in the 20 nm range or better have been reported for the Shintake and BINP BPMs. Centering stability better than ± 50 nm over 2 hours has been observed. However we are not aware of a common-mode-free cavity BPM that has been qualified for use in a cryogenic clean environment.

Re-entrant Cavity BPM

These are RF BPMs using coaxial resonant modes in a shorted coaxial structure. They have proven cryogenic and cleanroom compatibility as demonstrated in the TTF cryomodule. The signal at the output couplers have considerable common-mode signal. Careful monopole mode cancellation is required here; much of it is accomplished externally by RF hybrids in the processor electronics. A recent design should achieve 1 micron resolution. More R&D is required to demonstrate required resolution and stability.

Table 2. Main Linac BPM Pickup Options: Pros and Cons

Type	Pros	Cons
Reentrant Cavity	Proven cryo-compatibility Good bunch-bunch resolution	Unproven sub-micron resolution Unproven stability; depends on tuning in electronics module
Cavity	Proven resolution Expect excellent stability Good bunch-bunch resolution	Unproven cryo-compatibility

Beam Delivery System

Beam jitter to be kept less than 50% of the beam size in most of the BDS. To verify that the jitter requirement is met and to understand the sources of jitter if the requirement is not met, BDS BPMs must have resolution significantly better than half the beam size. We adopt a BPM single pulse resolution requirement of one-quarter of the beam size. Cavity BPMs are favored for most of the BPMs here for resolution, accuracy, and stability. The intra-train IP feedback BPMs are exceptions; these are likely to be stripline BPMs for ease of low-propagation delay processing, and for the 2 milliradian crossing angle scheme, the possibility of directional beam pickups.

Table 3. Beam Delivery System Position Monitor Requirements

Parameter	Requirement	Comments
Quantity	~400	
Aperture	Various sizes	
Resolution	$\sim \sigma/4$ ~250 nm	
Stability	<10 microns	long term
	< 1 micron / hour	Energy Spectrometer only
Temporal resolution	bunch-by-bunch	many places, assume all

A potential problem arises from the beam halo generated in the collimators. The center of gravity of this halo does not necessarily coincide with the position of the beam core. The BPMs will measure the position of the sum of beam core and halo position weighted by their relative intensities, while for optics tuning and feedbacks the core position is the relative quantity. Dedicated studies of these effects are required to estimate the magnitude and potential risks of this effect.

Injector Systems Beam Position Monitors

The beam position monitors in the electron and positron injectors have in comparison with the downstream systems relatively relaxed requirements. They are summarized in Table 4. Transverse beam dimensions are typically three orders of magnitude larger than in the downstream systems; these resolution requirements can easily be met with present BPM technology. A possible approach could be the use of stripline pickups for beamlines at ambient temperature and re-entrant or cavity pickups in the parts of the cold linac upstream of the damping rings (see main linac BPM description above). For the BPM's in the positron capture system special care has to be taken due to large particle losses and integrated radiation doses. Appropriate solutions exist.

Table 4. Injector BPM Requirements

Parameter	Requirements	Comments
Quantity	600	
Environment	Both ambient temperature and cryogenic	
Aperture diameter	40 mm – 100 mm	
Resolution	$< 100 \mu\text{m}$	
Precision	$< 100 \mu\text{m}$	
Time resolution	Better than 300 ns	Single bunch position has to be resolved for a bunch spacing of 300 ns

Damping Rings

Each of the three damping rings (one electron DR and two positron DRs) will be equipped with a number of BPMs corresponding to roughly four times the horizontal tune value. Most of the BPMs are needed for slow orbit measurement and control. The requirements for these BPMs are summarized in Table 5. Similar performances have been achieved in existing storage rings with button or stripline type pickups.

Table 5. Damping Ring Orbit BPM Requirements

Parameter	Requirements	Comments
Quantity	900	3 rings with $Q_x \approx 70$
Environment	Ambient temperature	
Aperture diameter	16/40/98 mm	Different apertures correspond to locations in wigglers, arcs and straight. Numbers taken from www-library.lbl.gov/docs/LBNL/570/45/PDF/LBNL-57045.pdf
Resolution	$0.5 \mu\text{m}$	
Precision	$< 100 \mu\text{m}$	
Roll error	$< 20 \text{ mrad}$	
Bandwidth	$> 100 \text{ kHz}$	

A small number of BPMs with fast signal processing will be needed longitudinal and transverse feedback systems. Their requirements are summarized in Table 6. The BPM pickup can be of the same type as the slow BPMs, i.e. button or stripline, but a fast readout integral to feedback electronics is required. Similar performances have already been achieved in existing storage rings.

Table 6. Damping Ring Feedback BPM Requirements

Parameter	Requirements	Comments
Quantity	9	3 BPMs for each of the 3 rings
Environment	Ambient temperature	
Aperture radius	20 mm	We assume that at least one of the feedback BPMs has to be located in the arcs for longitudinal feedback
Resolution	0.5 μm	
Precision	< 100 μm	
Time resolution	Better than 6ns	Single bunch position has to be resolved for a bunch spacing of 6 ns

R&D Required

- Develop Cryo-compatible cavity BPM, prove cleanability
- Prove stability and resolution capability of re-entrant cavity BPM
- Develop and prototype cavities, evaluate in cryomodules
- Develop and prototype electronics
- Study effects of beam halos/beam tails on interpretation of beam position data, set requirements on halo/tail generation.